Evaluation of Ductile-Brittle Transition of Electron Beam Welded Steels Using Small Punch Test(小型パンチ試験による鋼電子ビーム溶接部の延性脆性遷移評価)

著者	蓋 暁輝
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氏名	ガイ　ギョウキ 蓋　曉輝
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指導教官	東北大学教授　粉川　博之
論文審査委員	主査　東北大学教授　粉川　博之　東北大学教授　進藤　裕英 東北大学教授　川崎　亮

論文内容要旨

The precise evaluations of the fracture toughness and the ductile-brittle transition temperature (DBTT) of structural steel welds are very important for maintaining the reliability of the welding components. The DBTT evaluation of deep but narrow high energy beam welds, such as the electron beam (EB) welds or the laser beam (LB) welds by the conventional Charpy V-notch (CVN) impact test is not successful because crack often deviates from the fusion zone into the heat affected or unaffected base metal zones. To detect the ductile-brittle transition behavior of the welds, the further developed CVN tests including the 3-sided CVN test and the miniaturized CVN tests have been introduced. However, there are many limitations with these methods. For the 3-sided CVN test, the difference between the standard CVN-DBTT and the 3-sided CVN-DBTT doesn't show correlation among various materials. In the case of the miniaturized CVN tests, it has been observed that changes in transition temperature between the full and the miniaturized specimens varied with specimen size. Due to experimental difficulties, these tests were difficult, complex and expensive to be performed. Furthermore, the usage of the 3-sided CVN and miniaturized CVN specimen may be still restricted to be applied to the evaluation of the narrow welds, for it is usually still too large to be cut only from the weld metal. Thus these methods are not practically useful to the evaluation of the DBTT of the EB welds.

The small punch (SP) test was developed in the early 1980s as a method for evaluation of the materials fracture toughness. It has been widely applied to the nuclear reactor materials such as austenitic steels and low alloy ferritic steels. The previous researches have described the relationship between the DBTT estimated by the small punch test (*SP-DBTT*) and the DBTT measured by Charpy V-notch test (*CVN-DBTT*) as a linear equation (1) in absolute temperatures:

$$[SP-DBTT]=\alpha\times[CVN-DBTT](K) \tag{1}$$

where α is a correlation coefficient, which was reported to vary from 0.35 to 0.45 for the various steels. SP test has also been tried to evaluate the yield stress, the ultimate tensile strength, the ductility and the fracture toughness. The results have shown some agreement with those of the uni-axial tensile tests and the fracture toughness tests. However, there is little literature on the application of SP test to heterogeneous materials such as welds, especially those having narrow beads such as EB or LB welds.

In the present study, SP test technology was first applied to evaluate the ductile-brittle transition behavior of EB weld metals, with very narrow beads. Various aspects of the SP process, such as the load-deflection behavior, SP energy, the fractography and the specimen microstructures were investigated. The toughness was evaluated by measuring the DBTT according to the variation of SP energy. The SP test results were also compared with the CVN test results in order to extract their correlations, because the CVN test is widely used for industrial applications, and a huge sum of database of CVN-DBTT has been well established.

In Chapter 2, SP test was performed on a 490MPa strength steel commonly used for shipbuilding and it's EB welds. The welds contain narrow-deep weld penetrations and narrow heat affected zones. The codes of the four kinds of weld specimens were designated as E1-E4. The fusion zone width at the middle depth of the penetration varied in the range between 1.5mm and 4mm. The penetration increased with increasing the heat input of the welds in the order from E1 to E4. Base metal had a microstructure of polygonal ferrite comprising pearlite, while all of EB weld metals indicated bainitic microstructures.

The effects of the specimen thickness, specimen orientation, and loading speed on the SP energy were first investigated to ensure the precise evaluation. The results show that SP energy depends on specimen thickness, and that the thickness effect on the SP energy varies significantly with temperatures. The tendency of brittle fracture increased with increasing the specimen thickness. To improve the measurement accuracy of SP energy, it is important to minimize the specimen thickness tolerance. No obvious difference in the SP energy was found within the load speed range from 0.1 to 200 mm/min, except that some serration was observed frequently in the load-deflection curves at the load speed higher than 1 mm/min (16.7 μm/s) at low temperatures. The effect of the specimen orientation on the SP energy was not found for the material detected in this study, it can be therefore negligible in base and weld metal specimens.

The temperature-dependence of the SP energy for each weld showed clear ductile-brittle transition, as shown in Fig.1, where the fitting lines are estimated by Weibull distribution. The Weibull estimation is an effective method for evaluating the *SP-DBTT* for dealing with the scatter in measured SP energy values. The SP energy of each weld indicates a fluent transition from a lower energy to a upper energy as the temperature is increased. Especially, the ductile-brittle transition behaviors are evidently examined for the E1, E2 weld metals, while it could not been examined by the standard CVN test. The *SP-DBTT*, which is judged from the relationship between the SP energy and the temperature, increases in the order of E1, E2, E3 and E4, i.e., the lower the welding heat input, the lower the *SP-DBTT*. This is thought of attributing to the lath size of the ferrite in the microstructure. With the heat input lowered from E4 to E1, size of the ferrite in the weld metal microstructure would decrease correspondingly. The smaller lath size of the ferrite generally results in the lower DBTT. *SP-DBTT* of the base metal is the lowest.

The load-deflection curves and the fractographies of the SP-tested specimens also supported the ductile-brittle transitions. The scanning electron micrographs of the appearances and crack surfaces of the E1 and E4 welds SP-tested showed typical ductile fractures at 298 K, in contrast with the cleavage fractures observed at 77K. The SEM photographs of E1 and E4 after punching at transition temperatures showed that the fracture surfaces of the specimens included the features of both dimple and cleavage facets. It reveals that the fracture mode is a transition mode between ductile mode and brittle mode. Though the macroscopic fracture path and fracture texture are different between the SP test and CVN test specimens, microscopic fracture mechanisms of the two techniques are similar and possible to be correlated.

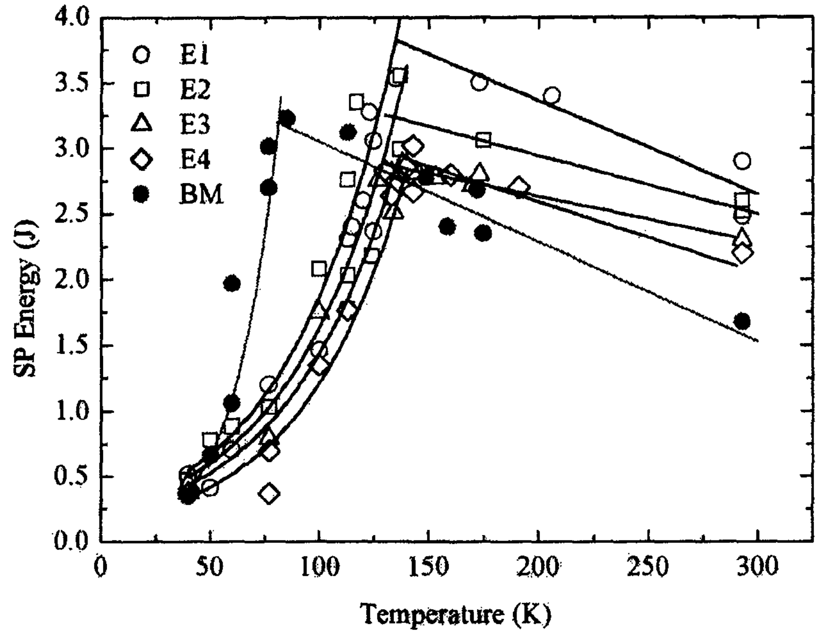

Fig. 1 Temperature-dependences of SP energy for the weld metals and the base metal.

In Chapter 3, SP tests were performed on various heat-treated steels, whose microstructures showed homogeneously-distributed lath morphologies. The initial indenting behavior of the specimen during the SP test showed that the loading behavior on the specimen in the initial elastic regime of the SP test has correlationship with the hardness test. The loading- unloading- reloading- deflection behavior in the SP test was examined. A large number of specimens tested at the room temperature, revealed that the unloading curves are affected by the Young's modulus of the tested steel similarly to the tensile test. By comparing the tensile properties (*0.2%YS*, *TS*) with the related SP values (P_Y/t_0^2 and P_M/t_0^2), the correlationship between the tensile properties and the related SP values were obtained. Also, the SP test results were compared to the CVN test results. The relationship between the *CVN -DBTT* and the *SP-DBTT* was confirmed with the proportional correlation coefficient of 0.42, which is identical to that obtained from the EB weld metals. SP test has a significant possibility for evaluating various mechanical properties such as the yield stress, ultimate tensile strength, hardness and the ductile to brittle transition temperature of steels simultaneously.

In Chapter 4, SP test was further applied to the DBTT evaluation of thermally simulated steels, which had been experienced the same cooling as the EB weld metals but were homogeneous in microstructure. The microstructure of the thermally simulated steels was similar to the microstructure of the weld metals with lath morphologies. The ductile-brittle transition behaviors were detected from the thermally simulated steels, and were consistent with those of the EB weld metals. The correlation between the *SP-DBTT* and the *CVN-DBTT* was quantified.

Since the fusion zone of the EB weld is narrow in width, the specimen size is sometimes still too large to change the orientation and location of the specimen by applying the SP tests. A further miniaturized specimen is needed to enable the evaluation of the local toughness of the weld metals. In Chapter 5, TEM-disk-size small punch (TDSP) test, which has a smaller size in dimension than the conventional SP test was applied to the evaluation of the DBTTs of the EB weld metals and the base metal. The deformation and the ductile-brittle transition behaviors of the specimens at various temperatures were examined. The results of TDSP tests were similar to those of the conventional SP tests, i.e., the TDSP-DBTTs were coincident with the SP-DBTTs, and were correlated to CVN-DBTTs. The load-deflection behaviors of the specimens parallel and perpendicular to the welding direction were investigated. It showed that the specimen orientation did not affect the DBTT evaluation on the EB welds.

The correlation coefficient between the *SP-DBTT* and the *CVN-DBTT* is slightly smaller for base metal compared to that of welds (0.42). One of the possible reasons for this result may due to the apparent differences in grain size and grain morphology between the base metal and the EB weld metals.

The main conclusions of this study can be outlined as:

1. The temperature-dependence of the SP energy for each weld of 490 MPa strength steel showed clear ductile-brittle transition. The *SP-DBTT* correlated linearly to the *CVN-DBTT* with a correlation coefficient of 0.42 for the EBW specimens of 490 MPa strength steel. This correlation coefficient was found to be the same as that obtained on the various heat-treated steels and the thermally simulated steels of the weld metals, which feature the characteristic of microstructures with lath

morphologies. Therefore, this correlation coefficient can be used to estimate the standard *CVN-DBTT* by SP test, which provides the applicability of SP test to the toughness evaluation of narrow bead weld metals produced by electron beam welding.

2. The correlation coefficient between the *SP-DBTT* and the *CVN-DBTT* of the base metal were lower (0.35) than that of the EB weld metal due to the difference of the grain morphology. The grain size and grain morphology affect the DBTT of the base metal and EB welds, and also affect the coefficient between the TDSP test and the CVN test because the influence of grain morphology upon the CVN-DBTT is not nearly as significant as its effect on SP-DBTT.
3. SP test is possible to be used for evaluating various mechanical properties such as the yield stress, ultimate tensile strength, hardness and the ductile to brittle transition temperature of steels simultaneously.
4. The results of TDSP tests were similar to conventional SP tests and were correlated to CVN tests. TDSP test can be used to evaluate the local toughness of much smaller specimen of the EB welds.

The present paper has proved that SP and TDSP tests are practically useful methods to evaluate the DBTT of the weld metal with narrow bead, such as the electron beam weld, because the results of SP test SP-DBTTs can then be related to the numerous engineering data in the database of CVN-DBTTs of steels and welds. Furthermore, TDSP test may provide the possibility of evaluating the DBTT of microscopic regions such as the HAZ of the EB weld.

論文審査結果の要旨

近年、高エネルギー密度ビームを利用した溶接法の実用化が進み、厚鋼板の溶接にも広く適用さてはじめている。ビーム溶接法では溶け込みが深く溶融幅が狭い溶接金属が得られ、熱影響部が狭く溶接変形や残留応力が小さいなど多くの利点がある。一方、鋼溶接部の靱性評価は、工業的にはシャルピー衝撃試験がしばしば用いられる。しかし、鋼の高エネルギー密度ビーム溶接金属に対して通常のVノッチシャルピー衝撃試験を適用すると、ノッチを溶接金属部に入れても、溶接金属が狭いためにクラックが熱影響部や母材に逸れることがしばしばあり、溶接金属のみからのシャルピー衝撃値を得るのが困難で工業的に大きな問題となっている。そこで本研究では、微小領域の機械的特性評価法である小型パンチ（SP）試験を鋼電子ビーム溶接金属に適用し、機械的特性評価を試みた。特に、SPエネルギーの温度変化から延性脆性遷移温度(DBTT)を求め、標準シャルピー試験の場合との相関を調べ、SP試験による高エネルギー密度ビーム溶接部の工業的な靱性評価の可能性を検討した。論文は全編6章で構成されている。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、入熱量の異なる鋼の電子ビーム溶接金属に対して温度を40Kから室温の範囲で変化させてSP試験を行い、SPエネルギーの温度依存性から延性脆性遷移温度(SP-DBTT)を求め、標準シャルピー衝撃エネルギーの延性脆性遷移温度（CVN-DBTT）との間に、[SP-DBTT]=0.42[CVN-DBTT]なる比例の相関関係があることを示した。

第3章では、3種類の鋼に対して種々の熱処理を行い、靱性の異なる均質な試験片に対してSP試験と標準シャルピー試験を行ったところ、DBTTに対して第2章と同じ比例関係が得られた。これらの試験片がいずれもラス状組織を有することから、ラス状組織の鋼の場合には係数0.42の比例関係が成立すると考えられる。

第4章では、電子ビーム溶接の熱履歴を模擬した再現熱サイクルを与えた鋼に対してSP試験と標準シャルピー試験を行ったところ、同様に係数0.42の比例関係が得られたことから、均質熱サイクル材に対しても同様の相関関係が成り立つことを示した。

第5章では、さらに微小領域へのSP試験の適用可能性を検討するため、TEMディスクサイズ試験片を用いて電子ビーム溶接金属のTDSP試験を試みたところ、標準サイズSP試験とほぼ同じ結果が得られた。

第6章は本研究の結果をまとめた総括である。

以上要するに本論文は、高エネルギー密度ビーム溶接金属に対する簡便な相対的靱性評価法としてのSP試験の適用可能性を示しており、材料加工プロセス学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。